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BOOSTER CORRECTING MAGNETS

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A. Orbit Correction Requirements at Injection

The criteria for the specification of booster correction magnets are discussed. The requirements for correction magnets are based in part on magnetic measurements of the F and D Booster magnets and partly on estimates of errors as discussed in the design report[1]. For closed orbit corrections, tuning at injection, and suppression of horizontal-vertical coupling in the straight sections, a horizontal and vertical dipole, quadrupole, and skew quadrupole will be placed in each short and long straight section[1,2]. In addition, four long straight sections are available for programmed quadrupoles, and/or higher multipole magnets should they be necessary. For the purposes of the correction elements it has been assumed that the errors can be divided into two categories. These are dc errors, such as remanent field effects and stray fields which remain constant during the cycle and ac errors which can be assumed to be proportional to the proton beam momentum. The second category results from variations in effective length, magnet tilts and misalignments, etc. and, if necessary, will be corrected by realignment of the magnets.

The design of the correction elements has been based on compensating for the dc errors with the future possibility of pulsing them to higher field level, whereas the errors at low fields can be compensated for by the correcting magnets.

The dipoles are designed to introduce a bend of 1.4 cm in 10 m (the distance separating successive trim magnets) at injection. This requires a bending length of 3000 gauss-cm. The maximum aperture allowances made for closed-orbit errors, injection errors, $\Delta\nu$ tuning range, $\Delta n/n$ tolerance, plus an extra allowance, totals 1.4 cm. Although current regulation at injection is expected to be better than .1%, the dipoles could compensate for a relative field error 10 times this amount or $\Delta B/B$ = 1%. Also, other installations[3] have observed that with proper training of the magnets, the remnant fields could be reduced to less than 1 gauss. For the booster, this means that $\Delta B/B$ due to remnant fields could be reduced to less than .2%. The dipoles will be individually controlled and will be operated in a dc mode only.

Quadrupoles for Tuning at Injection

The defining requirement here is to provide for tune shifts of .6 at injection. This amount of shift can be obtained by a gradient of 8.9 g/cm ($\int B'd\ell$ = 220 gauss) in the quadrupoles in the long straight sections and 5.6 g/cm ($\int B'd\ell$ = 138 gauss) in the quadrupoles in the short straight sections.

There is a possibility of beam deterioration from space charge effects, since the vertical tune is reduced to 6.25 at injection and the half integral stop band at $\nu_y = 6.5$ is crossed later during the cycle. This may require removing the 13th azimuthal harmonic of gradient errors for the y motion. Separate control of all 48 trim quadrupoles would, of course, provide the greatest flexibility in producing any harmonic and phase that might be desired.

In order to determine whether or not one could power more than one quadrupole in series and still provide adequate 13th harmonic, the system was analyzed on the assumption that the gradient error in the D magnets was 1% and distributed so as to produce the widest possible stop band width. With this assumption it was found that the trim quadrupoles could be strung three in series or even 12 in series and still produce an adequate 13th harmonic to reduce the band width of the vertical stop band at 6.5. With 12 magnets in series all the odd harmonics appear with roughly equal strength. With three in series, one obtains the largest possible 13th harmonic with the exception of individual control of every magnet and, in addition, all harmonics are essentially zero except for those given by 8k-3, and 8k-5, k = 1, 2, 3, etc. The power supplies for the quadrupoles must be programmable, but only dc regulation is anticipated initially.

Sextupoles

DC magnetic measurements on the F magnet indicate that there is a .5kg/m^2 remnant sextupole component. This could be corrected by four dc sextupoles one foot long with a strength of 65 kg/m^2. Since this effect seems to be associated with remnant fields (it disappears completely at about 1500 gauss), it may be reduced considerably by magnet training as mentioned previously. Therefore, it is not intended to provide sextupoles initially.

Skew Quadrupoles

Twisting of the magnetic median plane, stray fields, and azimuthal fields lead to coupling of the horizontal and vertical oscillations. The coupled motion will be unstable if $\nu_x + \nu_y$ = integer (sum resonance). As mentioned earlier, the vertical tune may be in the vicinity of 6.3 due to space charge effects in which case $\nu_x + \nu_y = 13$.

The horizontal field component which is present in a twisted magnet can be compensated for by skew quadrupoles (i.e., the quadrupole part of the horizontal field) so that there is no net horizontal field present when summed around the ring. It would require skew quadrupoles (33 cm long) with a gradient of 2.4 g/cm to cancel the effect of all the F and D magnets being rotated 5 mrads assuming that the horizontal fields thus produced were in the same sense. This rather adverse situation is unlikely, of course, but it becomes somewhat impractical to construct quadrupoles with gradients much smaller than this. The 13th azimuthal harmonic should, in fact, be provided by the skew quadrupoles with variable phase to cancel this linear coupling resonance. The wiring scheme that was discussed for the quadrupoles would be also appropriate here.

The difference resonance which occurs when $\nu_x = \nu_y$ does not produce an unstable orbit, but when there is magnet twist present, the vertical and horizontal oscillations will none the less be coupled. This has been observed to lead to some disturbing effects when trying to tune the beam at other installations. To correct this, the zeroth harmonic is all that is necessary in the skew quadrupoles.

Other Considerations

Resonances of order $\geq$ 5 can, it seems, generally be ignored[4]. Fourth order sum resonances could give trouble under certain conditions although no such resonance has been pinpointed to date in the existing machines as causing trouble. There is a fourth order sum resonance right through the booster operating point. This would be driven by 27th azimuthal harmonic errors. The correction for such an effect would be obtained by higher multipole magnets, sextupole, or octupole for example. As has been the case at other installations, this and other nearby high order resonances are not expected to appear with any serious consequences, however, there is space available in four long straight sections should they be necessary.

It has been decided not to provide ac power to any of the correction magnets mentioned above initially. Furthermore, all of the corrections discussed so far take place at injection. It may turn out that fast quadrupoles to provide a rapid tune shift at transition are necessary. In the event that these and other programmed correcting magnets are required, they will be placed in available long straight sections.

B. Correcting Magnets

In addition to the field requirements stated above, the following factors were considered in the actual design of the magnets.

1. The magnets must be capable of being assembled around the outside of the vacuum pipe without disturbing the integrity of the vacuum system.

2. The maximum space available in the direction of the beam is 14" at each of the 48 desired locations and 8½" from beam center to top surface of the magnet support girder.

3. They should be air cooled, if possible, and air core to avoid hysteresis and remnant field problems.

4. Cost of both operation and construction should be minimized while at the same time maintaining $\int B d\ell$ in the dipoles and $\int B' d\ell$ in the quadrupoles to within 10% of the required values across the maximum good field width of 4.33" (required in the horizontal plane in the short straight section between two F-type magnets).

It can be seen that requirements 2) and 3) eliminate any consideration of individual iron core magnets. Requirement 1) eliminated the possibility of winding all four magnet types inside a steel cylinder much like field windings in an electric motor. Another scheme of individually powered poles was abandoned because the increased complexity in the switching and powering circuitry proved to be too costly. Because of the large number required one could not afford to have each individual winding carefully laid in place by hand, this led to considering random wound coils which could be assembled in sections around the beam pipe. A cross section of such an assembly is shown schematically in Figure 1. The questions to be answered were, of course, whether or not the maximum fields and uniformity requirements could be met.

For infinite cylinders of cross section shown in Figure 3, analytic expressions have been developed for the resulting two-dimensional fields[5]. Using these expressions, it was shown that certainly the maximum field requirements could be met without any special kind of cooling. Magnetic measurements showed that the effect of the ends was to make the ratio of (magnetic length)/(geometric length) = .7. Furthermore, it was shown that a current density of 77.5 amps/cm (500 amps/in^2), which corresponds to equal costs for copper and operating for 10 years was feasible in these magnets. Based on two-dimensional calculations, preprototype magnets were wound at ANL and tested. The results showed that heating would be no problem even when all four magnets were assembled as shown in Figure 1 and were run at full power continuously. However, the field uniformity tests showed something less than was desired. It should be noted here that two different types of end windings were tried. One type had the ends turned up so they pointed away from the beam. This type did provide a slightly more uniform field than the type where the ends laid flat on the pipe. The main disadvantage of the turned up ends was in the difficulty of winding. In addition, it makes for a more bulky package and would preclude the possibility of adding a concentric iron cylinder around the outside for added field strength and uniformity should it be necessary. It was shown by using an expression given by Halbach[8] that the field strength increased by ~80% for the outer dipole and ~10% for the quadrupole with an iron cylinder added. It was shown by measurement that the uniformity was improved by about 20%.

Since it would have been highly impractical to attempt to achieve better uniformity through trial and error construction of many magnets, it was decided to calculate the field exactly. Following a suggestion by Halacsy[9], the differential form of Ampere's law

$$d\vec{B} = \frac{I}{C} \frac{\vec{d\ell} \times \vec{X}}{|\vec{X}|^3} \tag{1}$$

was programmed to add up the fields due to current elements $I\vec{d\ell}$ in the magnet. There were three different geometrical shapes to consider; namely, a circle, straight line, and a curve connecting the first two. The field from the line was determined from an integrated form of eq (1) to reduce computer time. The program was checked against two dimensional calculations by computing the field for various x at the center of a very long magnet. The agreement was within 2 parts in 10^3. It was also checked against a hand calculation of the field along the axis $x = y = o$, using one current loop and assuming sharp corners, again with good agreement.

Using this program, the final designs were completed. The calculated field uniformities are shown in Figures 2 and 3. The electrical properties are listed in Table 1. Complete descriptions of the magnets can be found in various NAL drawings and specifications[10]. We mention only briefly here the basic construction of each type of magnet. It was found that random winding on a cylindrical fixture did not work well for the dipoles although this procedure is quite satisfactory for winding a 1/4 section of a quadrupole. By using square wire the dipoles could be wound in flat layers, then pre-rolled to the proper radius, electrically connected and bonded together to form a half section of a dipole. Radiation resistant epoxy and insulation were specified.

It is worth mentioning perhaps just how the results of minimizing the field variation over the gap by using two-dimensional calculations differed from the three-dimensional calculations. Essentially the variation was minimized in the two-dimensional case by adjusting sector angles (and radii in case of a two-step sector) with a function minimization program. An obvious starting choice for the two dimensional dipole sector angle is 60°, since this makes the sextupole field term zero (and certain other higher order terms as well). The most uniform field over the required region would require a sector angle between 63°-65° on the basis of two-dimensional calculations. On the contrary the three-dimensional program showed that the best sector angle was less than 60° (53°-56° for dipoles with an aspect ratio (mean diameter)/(maximum outside length) = .6. It was also observed that the addition of an extra step such as that found on the inner dipole, Figure 1, did not appreciably flatten the quantity $\int Bd\ell$, although it did make B(x) across the gap at the center of the magnet and the effective magnetic length L(x) more uniform. Nevertheless, by varying the angles of several steps, one should be able to achieve almost any degree of uniformity. It would not be practical to use the three-dimensional program in conjunction with a function minimization routine for a magnet with very many turns. However, the sector angle is the most sensitive parameter for altering the quantity $\int B(x)d\ell$, while the thickness of the windings has a much smaller effect. Therefore, one could do preliminary designs with a single layer of windings at the mean diameter, thereby having only a few loops. In this case a function minimization routine which would vary the sector angles to find the minimum of say

$$\sum_{i,j} \left\{ \frac{\int B(x_i, y_j)dz - \int B(o, o)dz}{\int B(o, o)dz} \right\}^2$$

would be feasible.

Summary

The capability of making corrections to the Booster Orbit at first turn on has been restricted to dc corrections. However, space is available, as well as service power and cooling water, for additional correcting magnets should they be necessary to increase the beam instensity later on. The capability of a tune shift at ejection of .15 was not provided as originally conceived[1], since no essential reason for its existence survived a review of the orbit corrections requirements. The final design of the correcting magnets satisfies all the requirements previously mentioned. Unfortunately, a good magnet model has not as yet been constructed so no comparison is available between calculated and measured data. However, three-dimensional calculations were made on a prototype dipole which was constructed in a manner similar to the final designs. The measurement of a 4% variation in $\int B d\ell$ due to sextupole was verified by these calculations.

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   Inner Dipole #0326-MD-2767
   Outer Dipole #0326-MD-2763

Table 1 CORRECTING MAGNETS

Magnet	Inner Radius	Outer Radius	Wire Size	Turns/ Section	Total Resistance	Current	$\int B d\ell$ or $\int B' d\ell$
Quadrupole	5.87	6.22	18 RD	259	14.1	1.01	220 g
Skew Quadrupole	7.14	7.40	20 RD	118	11.1	.27a	24 g
Inner Dipole	7.62	10.0	13 SQ	496	4.03	3.24a	3000 g-cm
Outer Dipole	10.16	12.57	11 SQ	455	2.32	5.6 a	3000 g-cm

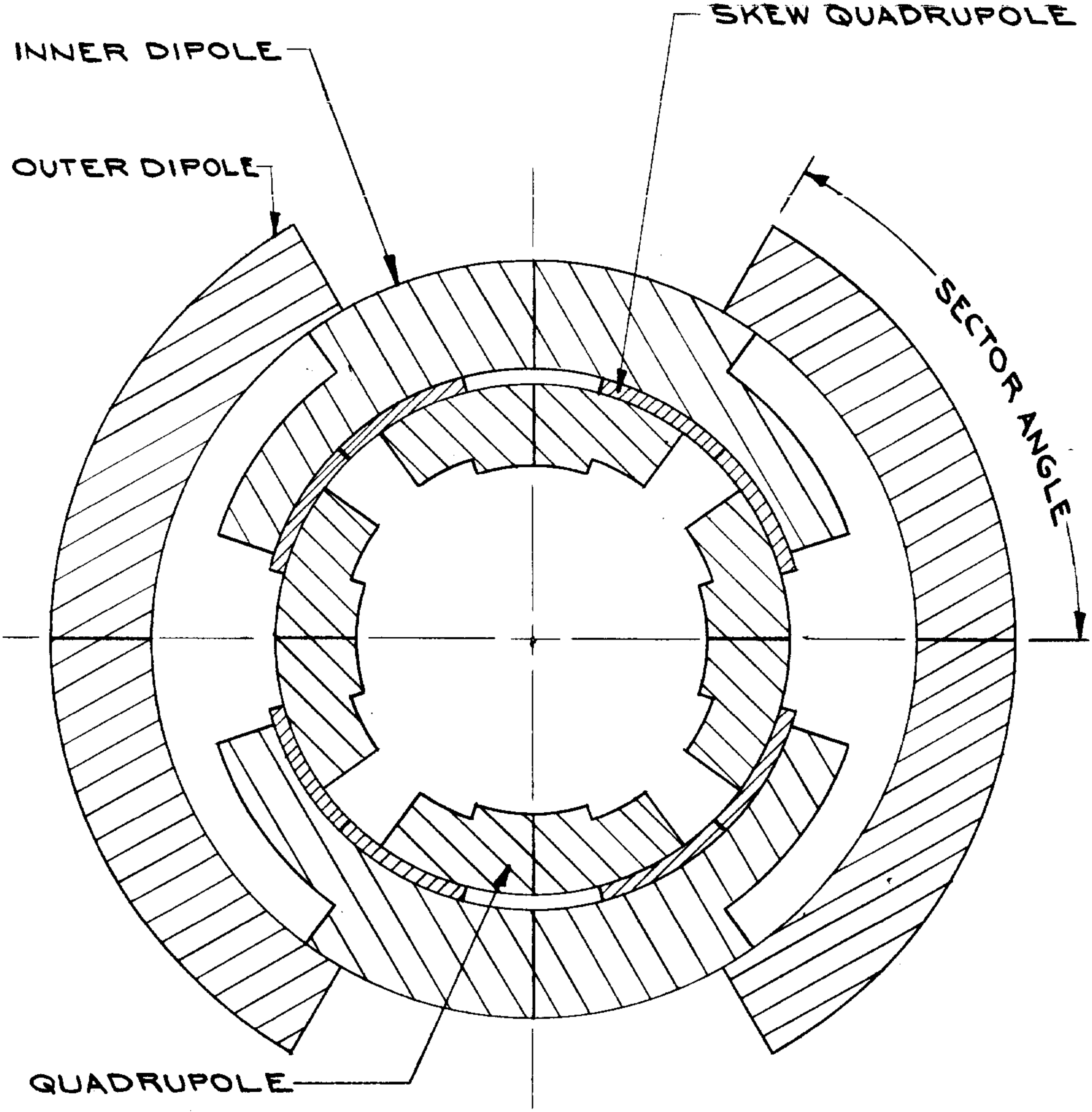

FIGURE 1

Cross-sectional view of a typical assembly of four trim magnets.

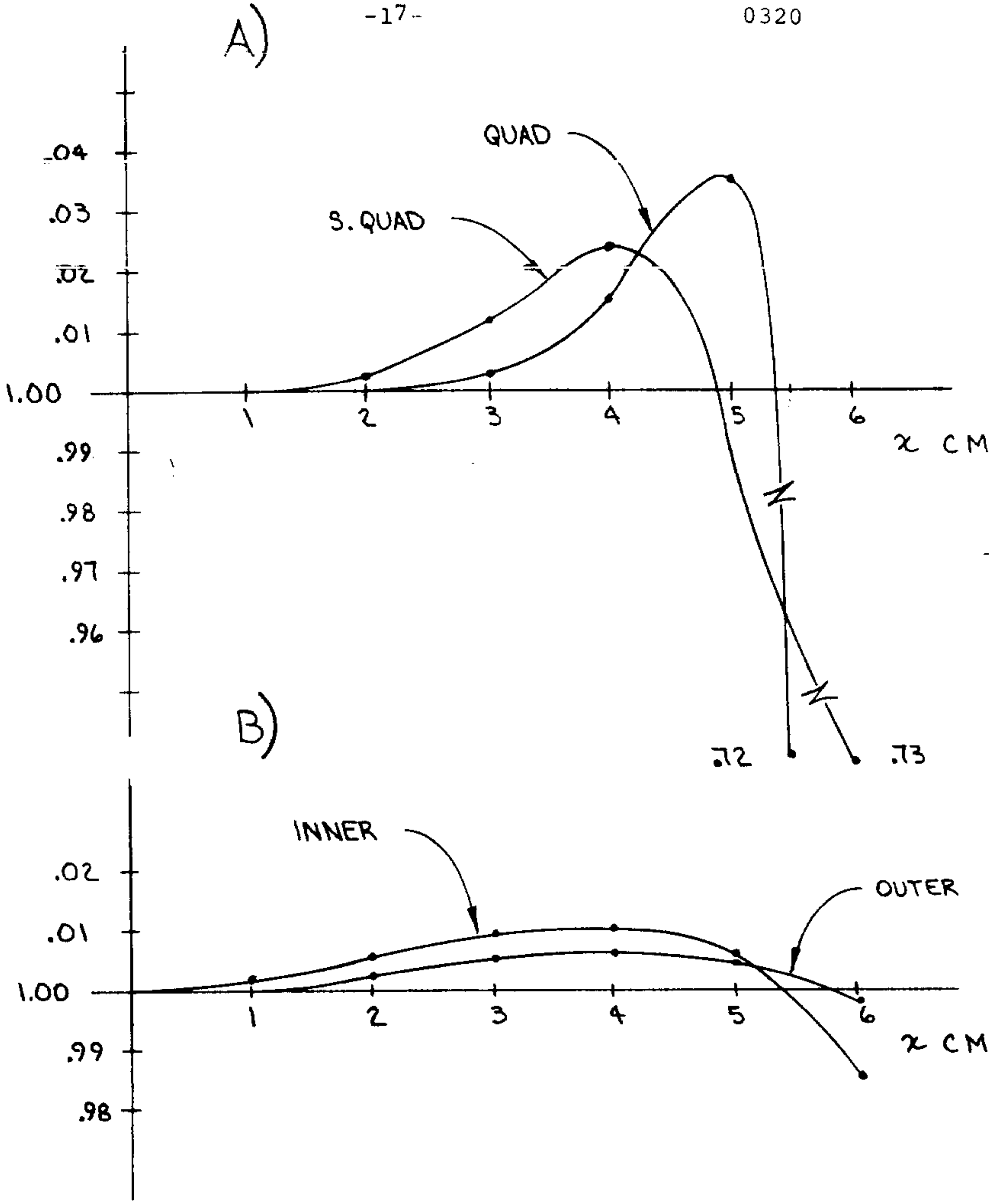

FIGURE 2

A) $\int B'(x,o)dz/\int B'(o,o)dz$ for the quadrupoles.

B) $\int B(x,o)dz/\int B(o,o)dz$ for the inner and outer dipoles.

GOOD FIELD AREAS AT INJECTION

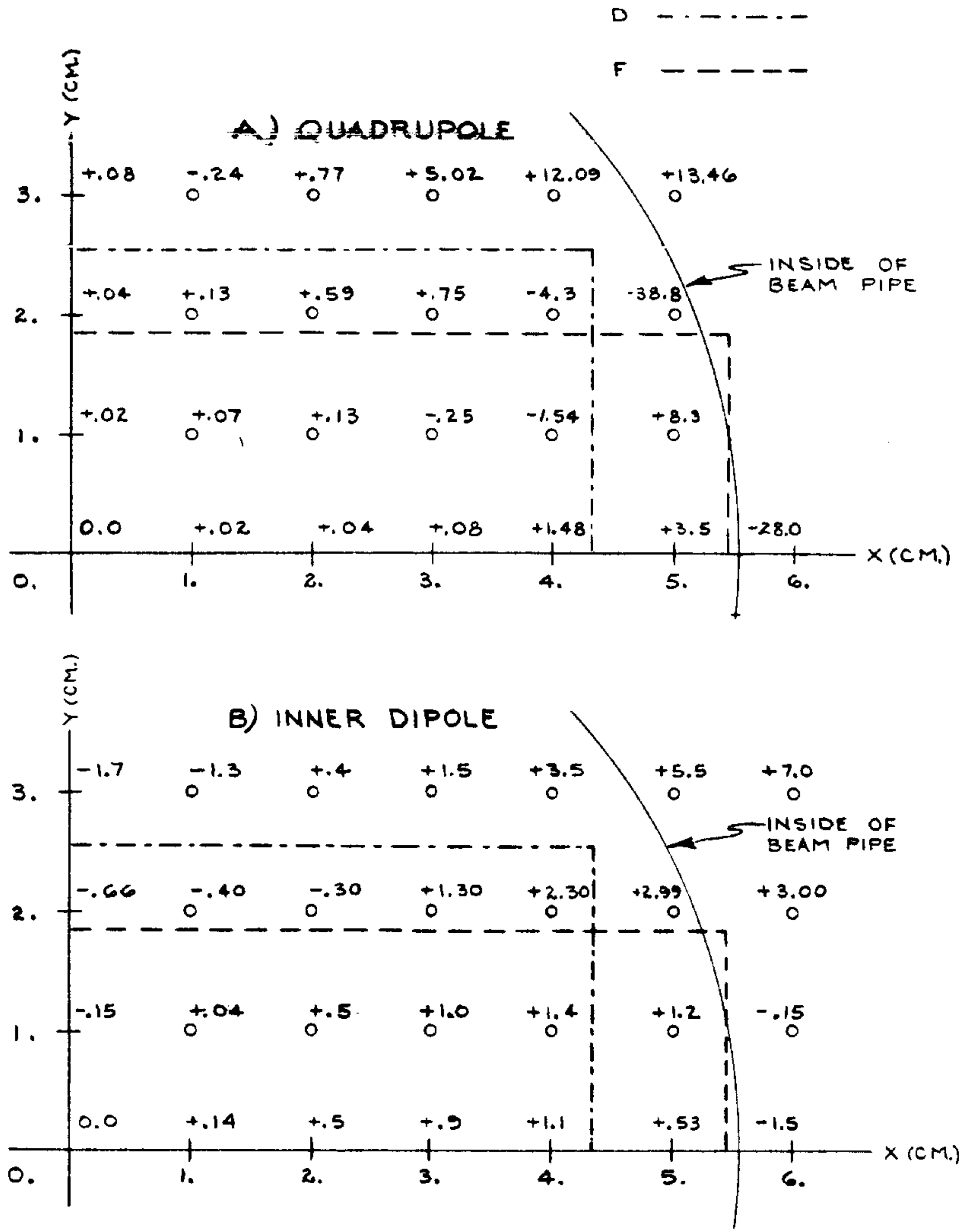

FIGURE 3

The percentage difference in the calculated values of gradient length and bending length for the trim quadrupole and inner dipole.

A) $\left[\left(\int B'(x,y)dz - \int B'(o,o)dz\right)/\int B'(o,o)d\right] \times 100$

B) $\left[\left(\int B(x,y)dz - \int B(o,o)dz\right)/\int B(o,o)dz\right] \times 100$

BY. ______________ DATE ________